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Gamma-Ray Bursts - When Theory Meets Observations

Tsvi Piran

Racah institute for Physics,
The Hebrew University, Jerusalem Israel 91904

Abstract.
Gamma-Ray Bursts (GRBs) are the brightest objects observed. They are also the most relativistic objects known so far. GRBs occur when an ultrarelativisitic ejecta is slowed down by internal shocks within the flow. Relativistic particles accelerated within these shocks emit the observed gamma-rays by a combination of synchrotron and inverse Compton emission. External shocks with the circumstellar matter slow down further the ejecta and produce the afterglow, which lasts for months. Comparison of the predictions of this fireball model with observations confirm a relativistic macroscopic motion with a Lorentz factor of $\Gamma \geq 100$. Breaks in the light curves of the afterglow indicate that GRBs are beamed with typical opening angles of a few degrees. The temporal variability of the gamma-rays signal provide us with the best indirect evidence on the nature of the "internal engine" that powers the GRBs and accelerates the relativistic ejecta, suggesting accretion of a massive disk onto a newborn black hole: GRBs are the birth cries of these black holes. Two of the most promising models: Neutron Star Mergers and Collapars lead naturally to this scenario.

INTRODUCTION

Gamma-Ray bursts - GRBs, short and intense bursts of γ-rays arriving from random directions in the sky were discovered accidentally more than thirty years ago. During the last decade two detectors, BATSE on CGRO and BeppoSAX have revolutionized our understanding of GRBs. BATSE has demonstrated [1] that GRBs originate at cosmological distances in the most energetic explosions in the Universe. BeppoSAX discovered X-ray afterglow [2]. This enabled us to pinpoint the positions of some bursts, locate optical [3] and radio [4] afterglows, identify host galaxies and measure redshifts to some bursts [5].

Since their discovery GRBs were among the prime topics of the Texas Symposia. The high energy release and the rapid time scales involved suggested immediately association with relativistic compact objects. The discoveries of BATSE and BeppoSAX confirmed these expectations. These observations have established the Fireball model demonstrating that GRBs are the most relativistic objects known so

far: GRBs involve macroscopic ultrarelativistic flows with Lorentz factors $\Gamma \geq 100$. Furthermore, while the "central engines" that drive the relativistic flow and power the GRBs are hidden we have excellent evidence that they involve accretion onto a newborn black hole. GRBs are the birth cries of these black hole.

I review, here, the recent progress in our understanding of GRBs, emphasizing, as appropriate for this conference, their relativistic nature. I begin, in section I with a brief tribute to the 7th Texas symposium. This was the first Texas meeting after the discovery of GRBs was announced and GRBs were the highlight of the discussion there. I continue in section II with a brief exposition of the Fireball model (see [6,7] for details), confronting its predictions with the observations. In III I summarize the implication of the fireball model to the "inner engines". Concluding remarks, further predictions and open questions are discussed in section IV.

I THE 7TH (NEW YORK) TEXAS SYMPOSIUM

GRBs were the hightlight of the Seventh (New York) Texas symposium that took place in 1974. Five out of the 57 talks were devoted to GRBs (this record was repeated only in this symposium with 3 out of 29 talks): Two observational reviews, a theoretical review, a theoretical model and even a description of an automated system for searching for optical transients accompanying GRBs!

M. Ruderman [8] reviewed the theory[1]. emphasizing the *compactness problem*: If GRBs are cosmological then the energy budget and the time scales seem to be incompatible with the observed non thermal spectrum of the bursts. The argument is simple: the variability time scale, δt, imposes an upper limit on the size ($R \leq c\delta t$). The observed flux and the assumed (cosmological) distance determine the energy. Together these yield an extremely large lower limits on the photons density within the source and on the optical depth for pair creation by the energetic photons. Pairs would be copiously produced and the source would be optically thick. The observed optically thin spectrum is impossible. Ruderman points out, however, that relativistic effects would change this conclusion. If the source is moving relativistically the relations between the time scale and the implied distance are modified (by a factor of Γ^2). Furthermore, photons that are observed with energy below 500ΓkeV have energy below 500keV in the source rest frame and could not produce pairs. These ideas lay the foundation for the current Fireball model. Recent observations have indeed confirmed ultrarelativistic motion in GRBs, showing at least in one case $\Gamma \geq 100$.

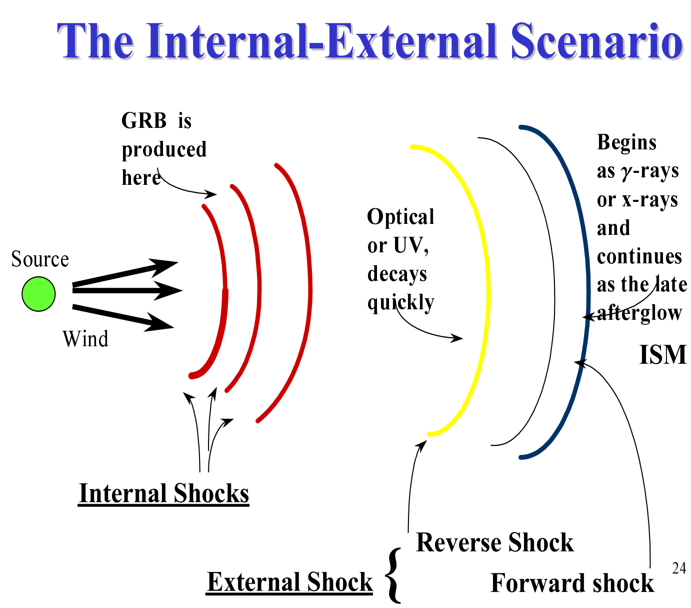
[1] This review enumerates more than thirty models proposed during the short time passed since the announcement of the discovery. It is remarkable (Ruderman, 1998, private communication) that today we know that none of these models is even remotely relevant.

II THE FIREBALL MODEL, PREDICTIONS AND CONFIRMATIONS

One can never prove a scientific theory. However we gain confidence in a theory when its predictions are confirmed by observations. I discuss, here, the predictions of the Fireball model (specifically of the Fireball-Internal-External shocks model) and their confirmation by numerous observations. My goal is to demonstrate the success of this model. While some of the specific observations could certainly be interpreted within other theories I strongly believe that the bulk of those observations tell us that this is the correct model.

The Fireball model asserts that GRBs are produced when the kinetic energy (or Poynting flux) of a relativistic flow is dissipated by shocks[2]. These shocks accelerate electrons and generate strong magnetic fields. The relativistic electrons emit the observed γ-rays via synchrotron or SSC. There are two variants of this model: The External Shocks model [9] assumes that the shocks are between the relativistic flow and the surrounding circumstellar matter. The Internal Shocks model [10,11] assumes that the flow is irregular and the shocks take place between faster and slower shells within the flow. According to the Internal-External shocks model [12] both kinds of shocks take place: Internal shocks are responsible for the GRB while external shocks produce the longer lasting afterglow (see Fig. 1) . Both shocks occur at relatively large distances ($10^{13} - 10^{14}$cm for internal shocks and $10^{14} - 10^{16}$cm for external shocks) from the source that generates the relativistic

[2] Given the low densities involved these shocks, like SNR shocks, must be collisionless.



flow. The observed radiation from the GRB or from the afterglow reflects only the conditions within these shocks. We have only indirect information on the nature of the "inner engines".

Fig. 1 depicts a schematic picture of the Internal-External shocks model. An inner engine produces an irregular wind. The wind varies on a scale δt and its overall duration is T. The variability scale δt corresponds to the variability scale observed in the GRB light curve [13] thus, $\delta t \sim 1$ sec. Internal shocks take place at $R \approx \delta t \Gamma^2 \approx 3 \cdot 10^{14}$cm $(\delta t/1\ sec)(\Gamma/100)^2$. External shocks shocks become significant and the blast wave that propagates into the circunstellar matter and produces the afterglow begins at $\sim 10^{16}$cm (see [14,6] for details). At this initial stage there is also a short lived reverse shock that propagates into the ejecta. This reverse shock is responsible to the prompt optical emission observed in GRB990123.

I review now the predictions of this model and confront them with observations.

• **Relativistic Motion - Predictions:** Relativistic motion is the key ingredient of the Fireball model. Relativistic motion arises naturally (a Fireball forms) when a large amount of energy is produced in a compact region with $E/Mc^2 \gg 1$ [15–17]. This relativistic motion overcome the compactness problem. Various estimates [18–21], of the Lorentz factor Γ based on the compactness problem lead to comparable values, $\Gamma \sim 100$, (see [21] for a critical review).

$\star$ **Relativistic Motion - Observations I:** The radio afterglow observations of GRB 970508 provided the first verification of relativistic motion. The radio light curve (in 4.86Ghz) variesd strongly during the first month. These variations died out later. Even before this transition Goodman [22] interpreted these variations as scintillations. The observation of a transition after one month enabled Frail et al., [4] to estimate the size of the afterglow at this stage as $\sim 10^{17}$cm. It immediately follows that the afterglow expanded relativistically. Additionally, the source is expected to be optically thick in radio [23] leading to a ν^2 rising spectrum at these frequencies. The observed flux from the source enables us (using the black body law) to estimate the size of the source. As predicted the radio spectrum increases like ν^2. The size estimated with this method agrees [4] with the one derived by the scintillations estimate implying as well a relativistic motion.

• **The Afterglow - Predictions:** The Afterglow - lower frequency emission that follows GRBs was one of the earlier predictions of the Fireball model [24–27]. Paczynski and Rhoads [24] predicted radio afterglow on the basis of the analogy between external shocks and SNRs. Later Meszaros and Rees [25,26] performed detailed calculations of multi-wavelength afterglow. Vietri [27] predicted soft x-ray afterglow as a test for the external shocks model. These predictions were done in the context of the external shocks model. According to this model the GRB arises due to a shock between a relativistic flow and a circumstellar medium. In this case the emission observed at time t_{obs} arises when $t_{obs} \approx R/2\Gamma^2$. Later emission is related to lower Γ (and larger emission radii) and hence to lower observed frequencies. This afterglow would be a direct extrapolation of the GRB and its basic features should be strongly correlated with the properties of the corresponding GRB.

The theory of the afterglow is well understood. Blandford and McKee [28] have

worked out (already in the seventies!) the theory of an adiabatic relativistic blast wave. They show that (as long as the flow is ultrarelativistic, $\Gamma \gg 1$), the blast wave is self similar, the relativistic analog of the well known Sedov-Taylor solution. Electrons are accelerated to relativistic velocities by the shocks and their interaction with the magnetic field leads to synchrotron radiation. This provides an excellent model for the observed emission [29]. Overall we have a simple theory characterized by five parameters: the total energy, E_0, the ambient density, n_0, the ratio of the electrons and magnetic fields energy density to the total energy density, ϵ_e, ϵ_B and the exponent of the electrons' energy distribution function p. An additional sixth parameters, the exponent of the circumstellar density distribution, n, arises in cases when the external matter density ($\rho \propto r^{-n}$). Most notable is $n = 2$ corresponding to a pre-GRB wind expected in some models [30]. This rather simple theory predicts a robust relations between α and β the exponents describing the flux as a function of frequency, $F_\nu \propto t^{-\alpha}\nu^{-\beta}$. At the high frequencies, above the cooling frequency, we have (for $n = 0$), $\alpha = (3p - 2)/4$ and $\beta = p/2$.

$\star$ **The Afterglow - Observations:** On Feb 28 1997, in a wonderful anniversary celebration for SN87A, BeppoSAX detected x-ray afterglow from GRB 970228. The exact position given by BeppoSAX led to the discovery of optical afterglow [3]. Radio afterglow was detected in GRB 970508 [4]. By now more than thirty x-ray afgterglows have been observed. About half of these have optical and radio afterglow as well and in most of those the host galaxy has been discovered.

Most x-ray and optical afterglow decay as power laws with $\alpha \sim 1.2$ and $\beta \sim 1.2$, in excellent agreement with the predictions of the simplest afterglow model: An adiabatic Blandford-McKee hydrodynamics with Synchrotron emission [29]. As α and β are determined by p the electron's distribution power law index, these observations suggest that as predicted [29,31], $p \approx 2.5$ and it is fairly invariant from one burst to another [32]. A simultaneous spectral fit for GRB980508, all the way from the radio to the x-ray also agrees with this picture [33].

$\bullet$ **The GRB-Afterglow Transition - Predictions:** The rapid time variability seen in most GRBs cannot be produced by external shocks [12,34]. This leaves internal shocks as the only viable model! Shortly before the discovery of the afterglow from GRB970228, Sari and Piran [12] pointed out that afterglow should arise also within the internal shocks scenario. The efficiency of the internal shocks depends on the parameters of the flow, most specifically on the variability of the Lorentz factor between different shells [13,35]. Even in the most efficient cases a significant fraction of the energy remain as kinetic energy. Sari and Piran [12] suggested that this energy would be dissipated later by interaction with the surrounding matter and produce an afterglow. Within this Internal-External shocks model the GRB is produce by internal shocks while the afterglow is produced by external shocks. The predictions of this model for the afterglow are similar to those of the External shocks model. However, a critical difference is that here the afterglow is not an extrapolation of the GRB.

The internal shocks take place at a distance $R_{IS} \sim \delta t \Gamma^2 \sim 10^{14}$cm. These shocks last as long as the inner engine is active. The typical observed time scale for this

activity ~ 50sec (for long bursts) and ~ 0.5sec (for short ones). External shocks begin at $R_{Ex} \sim 10^{16}$cm. If $R_{Ex}/\Gamma^2 \leq T$ this happens while internal shocks are still going on and the afterglow overlaps the late part of the GRB. At the early time the afterglow emission peaks in the high x-rays contributing also to the observed γ-ray flux. We expect, therefore, a transition within the GRB from hard (pure GRB) to softer and smoother (GRB and afterglow) signal.

⋆ **The GRB - Afterglow Transition - Observations:** The extrapolation of the x-ray afterglow fluxes backwards generally does not fit the γ-ray fluxes. Moreover there is no direct correlation between the γ-ray fluxes and the x-ray (or optical) afterglow fluxes. This result is in a nice agreement with the predictions of the Internal - External shocks scenario in which the two phenomena are produced by different effects and one should not expect a simple extrapolation to work.

The expected GRB afterglow transition have been observed in several cases. The first observation took place (but was not reported until much latter) already in 1992 [36]. Recent BeppoSAX data shows a rather sharp transition in the hardness that takes place several dozen seconds after the beginning of the bursts [37]. This transition is seen clearly in the different energy bands light curves of GRB990123 and in GRB980923 [38]. Connaughton [39] have averaged the light curves of many GRBs and discovered long and soft tails: the early x-ray afterglow.

• **The Prompt Optical Flash - Predictions:** The collision between the ejecta and the surrounding medium produces two shocks. The outer forward shock propagates into the ISM. This shock develops later into the self similar Blandford-McKee blast wave that drives the afterglow. A second shock, the reverse shock, propagates into the flow. This reverse shock is short lived. It dies out when it runs out of matter as it reaches the inner edge of the flow. While it is active, it is a powerful source of energy. Comparable amounts of energy are dissipated by the forward and by the reverse shocks [14]. We expect that the system is radiative at this stage, namely most of the energy converted by the shock is radiated away.

Sari and Piran predicted at the First Rome Meeting (Oct 1998) an intense (brighter than 11th magnitude) prompt optical flash from this reverse shock [40]. Previous work [26] done prior to the discovery of the afterglow considered various possibilities and estimated the magnitude of the prompt optical flash to be anywhere from 9th to 19th magnitude. The observations of the afterglow constrained severely the relevant models and the relevant parameter space. With the new data the constrained model led to a clear prediction with a narrow range of magnitude. At that time this prediction was almost conflicting with upper limits given by systems like LOTIS and ROTSE.

One prediction that was, unfortunately, missed: prompt radio emission from the reverse shock. This radio emission should be short lived, like the burst and should have initially an optically thick component that becomes optically thin later.

⋆ **The Prompt Optical Flash - Observations:** In Jan 23 1999 just three month after this prediction ROTSE recorded six snapshots of optical emission from GRB990123 [41] . Three of those were taken while the burst was still emitting γ-rays. The other three snapshots spanned a couple of minutes after the burst. The

second snapshot, taken 70sec after the onset of the burst corresponds to a 9th magnitude signal. A comparison of these optical observations with the γ-rays and x-rays light curves (see e.g. [7]) shows that the optical emission does not correlate with the γ-rays pulses. The optical photons and the γ rays are not emitted by the same photons [42,41]. The optical pulses peak some 70sec after the onset of the burst simultaneously with a late peak in the soft x-ray emission.

Radio observations of GRB990123 revealed a short lived radio pulse. This emission can be explained as coming from the reverse shock [42]. Using the parameters of the reverse shock derived from the optical flash Sari and Piran [42] estimated the magnitude of this radio emission. The theoretical curve and the observations are in excellent agreement (see e.g. [7]). Note that the theoretical curve was calculated just from the optical flash data and it was not "fitted" in any way to the observed data. While prompt optical flashes were not detected in other bursts, short lived radio flashes have been detected in GRB000926 and in GRB970828.

$\star$ **Relativistic Motion II - Observations:** The radio emission from GRB970508 showed relativistic motion in its afterglow. However, the significant observations were done one month after the burst and at that time the motion was only "mildly" relativistic with a Lorentz factor of order a few. The observations of GRB990123 enabled us to obtain three independent estimates of the ultrarelativistic Lorentz factor at the time that the ejecta hits first the ISM [42]. First the time delay between the GRB and the optical flash suggests $\Gamma \sim 200$. The ratio between the emission of the forwards shock (x-rays) and the reverse shock (optical) gives another estimate of $\Gamma \sim 70$. Finally the fact that the maximal synchroton frequency of the reverse shock was below the optical band led to $\Gamma \sim 200$. The agreement between these three crude and independent estimates is reassuring.

These observations provide us also with an estimate of the position of the external shocks, $\sim 10^{15}$cm at 70 seconds after the bursts. It is an impressive measurement considering the fact that the distance to this burst is $\sim 3.5Gpc$. The corresponding angular resolution is 10^{-13} or $\sim$ 50nanoarcsec.

• **Jets - Predictions:** With redshift measurements it became possible to obtain exact estimate the total energies involved. While the first burst GRB970508 required a modest value of $\sim 10^{51}$ergs, the energies required by other bursts were alarming, 3×10^{53}ergs for GRB981226 and 4×10^{54}ergs for GRB990123, and unreasonable for any simple compact object model. These values suggested that the assumed isotropic emission was wrong and GRBs are beamed. Significant beaming would of course reduce, correspondingly the energy budget.

Beaming was suggested even earlier as it arose naturally in some specific models. For example the binary neutron star merger has a natural funnel along its rotation axis and one could expect that any flow would be emitted preferably along this axis. The Collapsar model also requires beaming, as only a concentrated beamed energy could drill a whole through the stellar envelope that exists in this model.

Consider a relativistic flow with an opening angle θ. As long as $\theta > \Gamma^{-1}$ the forwards moving matter doesn't "notice" the angular structure and the hydrodynamics is "locally" spherical [43]. The radiation from each point is beamed into a

cone with an opening angle Γ^{-1}. It is impossible to distinguish at this stage a jet from a spherical expanding shell. When $\theta \sim \Gamma^{-1}$ the radiation starts to be beamed sideways. At the same time the hydrodynamic behaviour changes and the material starts expanding sideways. Both effects lead to a faster decrease in the observed flux, changing α, the exponent of the decay rate of the flux to: $\alpha = p/2$. Thus we expect a break in the light curve and a new relation between α and β after the break [44–46]. The magnitude of the break and the duration of the transition will change if the jet is expanding into a wind with r^{-2} density profile [47]. The break is expected to take place at $t_{jet} \approx 6.2(E_{52}/n_0)^{1/3}(\theta/0.1)^{8/3}$hr [45]. Recently numerical simulation [48] have shown that the break appears in a more realistic calculations, even though the numerical results suggest that the analytical model developed so far are probably too simple.

⋆ **Jet - Observations:** GRB980519 had unusual values for $\alpha = 2.05$ and $\beta = 1.15$. These values do not fit the "standard" spherical afterglow model[3]. However, these values are in excellent agreement with a sideway expanding jet [45]. The simplest interpretation of this data is that we observe a jet during its sideway expansion phase (with $p = 2.5$). The jet break transition from the spherical like phase to this phase took place shortly after the GRB and it was not caught in time. The light curves of GRB990123 shows, however, a break at $t \approx 2$days [49]. This break is interpreted as a jet break, corresponding to an opening angle $\theta \sim 5^o$. Another clear break was seen in GRB990510 [50,51].

The brightest bursts, GRB990123 and GRB980519 gave the first indications for jet like behaviour [45]. This suggested that their apparent high energy was due to the narrow beaming angles. A compilation of more bursts with jet breaks suggests that all bursts have a comparable energy $\sim 10^{51}$ergs and the variation in the observed energy is mostly due to the variation in the opening angles θ [52,53,32]

III THE INNER ENGINES

The Fireball model tells us how GRBs operate. However, it does not answer the most interesting astrophysical question: what produces them? which astrophysical process generates the energetic ultrarelativistic flows needed for the Fireball model? Several observational clues help us answer these questions.

• **Energy:** The total energy involved is large $\sim 10^{51}$ergs, a significant fraction of the binding energy of a stellar compact object. *The "inner engine" must be able to generate this energy and accelerate $\sim 10^{-5} M_\odot$ to relativistic velocities.*

• **Beaming:** Most GRBs are beamed with typical opening angles $0.02 < \theta < 0.2$. *The "inner engine" must be able to collimate the relativistic flow.*

• **Long and Short Bursts:** The bursts are divided to two groups according to their overall duration. Long bursts with $T > 2$sec and short ones with $T < 2$sec.

• **Rates:** GRBs take place once per $10^7(4/\theta^2)$yr per galaxy. *GRBs are very rare at about 1/1000 the rate of supernovae.*

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[3] A possible alternative fit is to a wind (n=2) model but with a unsual high value of $p = 3.5$

The Fireball Internal-External shocks model provides us with another key clue:

• **Time Scales:** The variability time scale, δt, is at times as short as 1ms. The overall duration, T, is of the order of 50sec. According to the internal shocks model these time scales are determined by the "inner engine". *$\delta t \sim$ msec suggests a compact object. $T \sim 50$sec is much longer than the dynamical time scale, suggesting a prolonged activity.*[4]*. This rules out any "explosive" model that release the energy in a single explosion.*

The internal shocks model requires two (or possibly three [55,56]) different time scales operating within the "inner engine". These clues, most specifically the last one suggest that GRBs arise due to accretion of a massive ($\sim 0.1 m_\odot$) disk onto a compact object, most likely a newborn black hole. A compact object is essential because of the short time scales. Accretion is needed to produce the two different time scales, and in particular the prolonged activity. A massive ($\sim 0.1 m_\odot$) disk is required because of the energetics. We expect that such a massive disk can form only simultaneously with the formation of the compact object. This leads to the conclusions that GRBs accompany the formation of black holes. This model is supported by the observations of relativistic (but not as relativistic as in GRBs) jets in AGNs, which are powered by accretion onto black holes. This system is capable of generating collimated relativistic flows even though we don't understand how.

An important alternative to accretion is Usov's model [57] in which the relativistic flow is mostly Poynting flux and it is driven by the magnetic and rotational energies of a newborn rapidly rotating neutron star. However this model seems to fall short by an order of magnitude of the energy required.

Several scenarios could lead to a black hole - massive accretion disk system. This could include mergers (NS-NS binaries [58,10], NS-BH binaries [59] WD-BH binaries [60], BH-He-star binaries [61]) and models based on "failed supernovae" or "Collapsars" [62–64]. Narayan et al. [65] have recently shown that accretion theory suggests that from all the above scenarios only Collapsars could produce long bursts and only NS-NS (or NS-BH) mergers could produce short bursts.

Additional indications arise from afterglow observations. One has to use these clues with care. Not all GRBs have afterglow (for example, so far afterglow was not detected from any short burst) and it is not clear whether these clues are relevant to the whole GRB populations. These clues seem to suggest a GRB-SN connection:

• **SN association:** Possible association of GRB980425 with SN98bw [66] and possible SN signatures in the afterglows of GRB970228 [67] and GRB980326 [68].

• **Iron lines:** have been observed in some x-ray afterglows [69]. Any model explaining them requires a significant amounts of iron at rest near those GRBs.

• **Association with Star formation:** GRBs seem to follow the star formation rate. GRB are located within star forming regions in star forming Galaxies [63,53].

• **GRB distribution:** GRBs are distributed within galaxies. There is no evidence for GRBs kicked out of their host galaxies [70,53] as would be expected for NS-NS mergers [10].

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[4] The ratio $\delta t/T \ll 1$ for short bursts as well [54]

All these clues point out towards a SN/GRB association and towards the Collapsar model. However, the situation is not clear cut. The association of GRB980425 with SN98bw is uncertain. There are alternative explanations to the bumps in the afterglows of GRB970228 and GRB980326 [71]. Iron is produces in Supernovae. But there is no simple explanation what is iron at rest doing around the GRB (see however, [72]). The association with star formation and the distribution of GRBs within galaxies is real but all that it indicates is short lived progenitors. One cannot rule out a short lived binary NS population [73] which would mimic this behaviour. Even worse, there are some indication that seem incompatible with the SN association:

• **No Windy Afterglow:** No evidence for a wind (n=2) in any of the afterglow light curves? Furthermore, most fits for the afterglow parameters show low ambient density [32,53].

• **No Jets:** Some GRBs dont show evidence for a jet or have very wide opening angles [32,53], this would be incompatible with the Collapsar model.

IV CONCLUSIONS, PREDICTIONS AND OPEN QUESTIONS

There is an ample observational support For the Fireball model. It also has several other predictions. The most interesting ones are those concerning the very early afterglow and the GRB-afterglow transition. The early afterglow phase is radiative and a detailed look at the first hour of the afterglow should show the radiative to adiabatic transition. It should also show (mostly in radio) small bumps corresponding to refreshed shocks [74] which would enable us to learn more on the nature of the flow produced by the "inner engine". With an operational HETE II and Swift in the not too distant future we hope that this crucial phase will be explored soon. Another prediction of a ring structure of the afterglow [75] will have to wait, however, to futuristic ultrahigh resolution detectors.

We know how GRBs are produced. We are less certain what produces them. We can trace backwards the evolution at the source from the observations of the emitting regions to an accretion disk - black hole system. The traces from this point backwards are less clear. Theoretical considerations [65] suggest that only Collapsars can produce the disk-black hole systems needed for long bursts while only NS-NS (or possibly NS-BH) mergers can produce the systems needed for short bursts. These conclusions are supported by the afterglows observations that suggest SN/GRB association for the long burst population. However, the picture is far from clear yet. While the information on the location of the bursts points out towards the SN connection the physical conditions within the afterglow indicate a low circumstellar density and does not show any indication for the almost inevitable pre explosion wind. The origin of the iron lines is still mysterious and confusing.

The Fireball model has still many open questions. Some are concerned with the physics of the fireball model: How do the collisionless shocks work? How are

the electrons accelerated and how are the magnetic fields amplified? How do jets expand sideways? What controls the "typical" emission to be in the soft γ-ray region? Other questions deal with more astrophysical issues like: What happens in all the cases (like WD-BH merger) in which a GRB almost form but the conditions are not exactly right? What distinguishes between the prgenitor of a GRB-"failed supernova" and the progenitor of a successful supernova with no GRB? Finally, we have, of course, the sixty four thousand dollars question: How does the "inner engine" accelerates the ejecta to relativistic velocities?.

REFERENCES

1. C. A. Meegan *et al.*, Nature, **355**, 143 (1992).
2. E. Costa *et al.*, Nature, **387**, 783 (1997).
3. J. van Paradijs *et al.*, Nature, **386**, 686 (1997).
4. D. A. Frail *et al.*, Nature, **389**, 261 (1997).
5. M. R. Metzger *et al.*, Nature, **387**, 879 (1997).
6. T. Piran, Physics Reports, **314**, 575 (1999).
7. T. Piran, Physics Reports, **333**, 529 (2000).
8. M. Ruderman, New York Academy Sciences Annals **262**, 164 (1975).
9. P. Meszaros and M. J. Rees, Ap. J., **405**, 278 (1993).
10. R. Narayan, B. Paczynski, and T. Piran, Ap. J. Lett., **395**, L83 (1992).
11. M. J. Rees and P. Meszaros, Ap. J. Lett., **430**, L93 (1994).
12. R. Sari and T. Piran, Ap. J., **485**, 270 (1997).
13. S. Kobayashi, T. Piran, and R. Sari, Ap. J., **490**, 92 (1997).
14. R. Sari and T. Piran, Ap. J. Lett., **455**, L143 (1995).
15. J. Goodman, Ap. J. Lett., **308**, L47 (1986).
16. B. Paczynski, Ap. J. Lett., **308**, L43 (1986).
17. A. Shemi and T. Piran, Ap. J. Lett., **365**, L55 (1990).
18. E. E. Fenimore, R. I. Epstein, and C. Ho, Astron. & Astroph. Supp., **97**, 59 (1993).
19. E. Woods and A. Loeb, Ap. J., **453**, 583 (1995).
20. T. Piran, in *Some Unsoved Problems in Astrophysics*, Eds. J. N. Bahcall and J. P. Ostriker, (Princeton University Press,1996).
21. Y. Lithwick and R. Sari, astro-ph /0011508 (2000).
22. J. Goodman, New Astronomy **2**, 449 (1997).
23. J. I. Katz and T. Piran, Ap. J., **490**, 772 (1997).
24. B. Paczynski and J. E. Rhoads, Ap. J. Lett., **418**, L5 (1993).
25. P. Meszaros and M. J. Rees, Ap. J. Lett., **418**, L59 (1993).
26. P. Meszaros and M. J. Rees, Ap. J., **476**, 232 (1997).
27. M. Vietri, Ap. J. Lett., **478**, L9 (1997).
28. R. D. Blandford and C. F. McKee, Physics of Fluids **19**, 1130 (1976).
29. R. Sari, T. Piran, and R. Narayan, Ap. J. Lett., **497**, L17 (1998).
30. R. A. Chevalier and Z. Li, Ap. J., **536**, 195 (2000).
31. R. Sari, R. Narayan, and T. Piran, Ap. J., **473**, 204 (1996).
32. A. Panaitescu and P. Kumar, to appear in Ap. J., (2001).

33. R. A. M. J. Wijers and T. J. Galama, Ap. J., **523**, 177 (1999).
34. E. E. Fenimore, C. D. Madras, and S. Nayakshin, Ap. J., **473**, 998 (1996).
35. F. Daigne and R. Mochkovitch, Mon. Not. RAS, **296**, 275 (1998).
36. R. A. Burenin *et al.*, Astron. & Astroph., **344**, L53 (1999).
37. E. Costa, Astron. & Astroph. Supp., **138**, 425 (1999).
38. T. W. Giblin *et al.*, Ap. J. Lett., **524**, L47 (1999).
39. V. Connaughton, in *The 19th Texas Symposium on Relativistic Astrophysics and Cosmology, Eds.: J. Paul, T. Montmerle, and E. Aubourg (CEA Saclay).* (1998).
40. R. Sari and T. Piran, Astron. & Astroph. Supp., **138**, 537 (1999).
41. C. W. Akerlofy *et al.*, Nature, **398**, 400 (1999).
42. R. Sari and T. Piran, Ap. J., **520**, 641 (1999).
43. T. Piran, in *AIP Conf. Proc. 307: Gamma-Ray Bursts* (1994), pp. 495.
44. J. E. Rhoads, Ap. J., **525**, 737 (1999).
45. R. Sari, T. Piran, and J. P. Halpern, Ap. J. Lett., **519**, L17 (1999).
46. A. Panaitescu and P. Mészáros, Ap. J., **526**, 707 (1999).
47. A. Panaitescu and P. Kumar, Ap. J., **543**, 66 (2000).
48. J. Granot *et al.*, astro-ph/0103038 (2001).
49. S. R. Kulkarni *et al.*, Nature, **398**, 389 (1999).
50. F. A. Harrison *et al.*, Ap. J. Lett., **523**, L121 (1999).
51. K. Z. Stanek *et al.*, Ap. J. Lett., **522**, L39 (1999).
52. D. A. Frail *et al.*, astro-ph/0102282 (2001).
53. S. R. Kulkarni, This volume (2001).
54. E. Nakar and T. Piran, astro-ph/0103192 (2001).
55. E. Ramirez-Ruiz, A. Merloni, and M. J. Rees, astro-ph/0010219 (2000).
56. E. Nakar and T. Piran, astro-ph/0103210 (2001).
57. V. V. Usov, Nature, **357**, 472 (1992).
58. D. Eichler, M. Livio, T. Piran, and D. N. Schramm, Nature, **340**, 126 (1989).
59. B. Paczynski, Acta Astronomica **41**, 257 (1991).
60. C. L. Fryer, S. E. Woosley, M. Herant, and M. B. Davies, Ap. J., **520**, 650 (1999).
61. C. L. Fryer and S. E. Woosley, Ap. J. Lett., **502**, L9 (1998).
62. S. E. Woosley, Ap. J., **405**, 273 (1993).
63. B. Paczynski, Ap. J. Lett., **494**, L45 (1998).
64. A. I. MacFadyen and S. E. Woosley, Ap. J., **524**, 262 (1999).
65. R. Narayan, T. Piran, and P. Kumar, astro-ph/0103360 (2001).
66. T. J. Galama *et al.*, Nature, **395**, 670 (1998).
67. D. E. Reichart, Ap. J. Lett., **521**, L111 (1999).
68. B. J. S. *et al.*, Nature, **401**, 453 (1999).
69. L. Piro *et al.*, Science **290**, 955 (2000).
70. B. J. S., S. R. Kulkarni, and Djorgovski, astro-ph **/0010176**, (2000).
71. A. A. Esin and R. Blandford, Ap. J. Lett., **534**, L151 (2000).
72. M. Vietri *et al.*, Ap. J. Lett., **550**, L43 (2001).
73. A. V. Tutukov and L. R. Yungelson, Mon. Not. RAS, **268**, 871 (1994).
74. P. Kumar and T. Piran, Ap. J., **532**, 286 (2000).
75. J. Granot, T. Piran, and R. Sari, Ap. J., **513**, 679 (1999).